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INTRODUCTION

In 1976, the Department of Energy (then known as ERDA) identified 17 candidate sites for detailed evaluation as potential sites for installation of large, horizontal axis Wind Turbines (WT), as part of its Wind Energy Program. From these initial sites, 4 were subsequently selected for installation of the WT known as Mod-0A. The design, fabrication and operation of these WTs is managed for the Department of Energy by the NASA Lewis Research Center (LeRC, 1978; Hunnicut, 1978). In the next section we briefly describe the Mod-0A WT. The following sections describe the meteorological data collected, show some of the analyses based on these wind data and discuss additional areas currently being investigated in relation to these data.

Mod-0A, CLAYTON, NEW MEXICO

The Mod-0A is a 200 kW version of the experimental 100 kW WT, Mod-0, located at Lewis Research Center's Plum Brook facility in Sandusky, Ohio (Glasgow, 1978). In November of 1977 the first Mod-0A WT was installed at Clayton, New Mexico. Since March 1978 this machine has been operated by the Clayton municipal utility in conjunction with the Wind Energy Project Office of Lewis Research Center.

Figure 1 shows a close-up of the Clayton Mod-0A. It is a two bladed, horizontal axis, rotor system operating at 40 rpm with the rotor located downwind from the tower. It has a 200 kW synchronous electric generator housed in the fiberglass nacelle on top of a 30 meter tower. Figure 2 is a cutaway drawing of the tower mounted equipment. The design specifications are given in Table I.

Of particular interest for this presentation are the four design wind speed ranges theoretically governing operation of the Mod-0A WT. The following windspeeds are all at hub height: (1) below 4.7 mps (1 mps = 2.2 mph); the blades are feathered (i.e., the WT is off) for lack of sufficient wind power; (2) 4.7-10.2 mps; the blades are pitched to extract maximum power; (3) 10.2-17.9 mps; the wind power extractable exceeds 200 kW and the blades are pitched slightly towards the feathered position to maintain 200 kW of power output; and (4) above 17.9 mps; the blades are fully feathered and the machine is shut down to prevent excessive loads on the machine. In addition, the entire structure is designed to withstand winds of up to 66 mps in a non-operating condition.

METEOROLOGICAL TOWER

A view of the Clayton installation which includes the meteorological tower is shown in Fig. 3. At Clayton, this tower has been instrumented for wind speed and direction at 9.1, 30.5, and 45.7 meters. Until recently the wind data for all the candidate sites, including Clayton, had been acquired on strip charts, digitized manually and analyzed on the basis of hourly averages (WSSI, 1978). Using these data we have calculated expected annual energy output for the Mod-0A WT, determined the cumulative frequency of occurrence of wind speeds at all 3 elevations and determined the validity of our wind velocity dependent shear profile formulation (Spera, 1979) as shown in Fig. 4.

This past year Battelle Pacific Northwest Laboratory has assumed responsibility for the maintenance, acquisition and preliminary analysis of the candi date site wind data. Thru their contractor they have changed to an all digital system and have also added four WT operational parameters, namely: nacelle direction, yaw error (e.g., instantaneous deviation of nacelle direction from local wind direction), power output and wind measured at the nacelle. In addition to providing long term monitoring of power performance, this will enable us to better evaluate the Mod-0A performance in response to wind gustiness in both amplitude and direction.

POWER PERFORMANCE

Many of our analyses involve only a few hours of data. For these data we often use Tukey's Schematic Plots (Tukey, 1977), as in Fig. 5, which shows alternator power as a function of wind speed at the nacelle for each revolution of the WT (Richards, 1978). Presumably, much of the scatter in the power output is attributable to the discrepancy between the very localized wind speed values that the anemometer senses as opposed to the wind over a 40 meter diameter disk to which the WT rotor responds (Golding, 1976).

CONTROL SYSTEM

Two additional factors are of interest to both the designer and the user of a WT. One is the extent of any loss of power due to the instantaneous misalignment of the WT with the wind. Another is the amount of time required for the startup of the WT whenever the wind velocity crosses into the operating range of the machine.

As mentioned earlier, the Mod-0A WT has a cut-in wind speed of 4.7 mps. This is a nominal value based on theoretical calculation of the minimum wind for which power would be produced. In practice, however, it takes from 4 to 10 minutes to bring the Mod-0A from a parked configuration to energy production in synchronization with the utility grid. Because of the spatial and temporal gustiness of the wind over such a time span, the following procedure has empirically evolved: (a) The wind speed signal is averaged (electronically) for one minute; (b) In low winds the WT is started when the wind reaches 5.8 mps and shut down if the wind speed falls to 4.5 mps; and (c) In high winds the WT is shut down if the wind reaches 17.8 mps and restarts when the wind speed drops to 15.7 mps. Even so, it is possible to produce a sequence of starts and stops

as in Fig. 6 which shows 6 start/stop cycles in 1 hour. This is undesireable not only because of the inefficiency of energy extraction, but also because of increased wear on the entire WT.

We are presently investigating the applicability of Time Series Analysis for forecasting wind speed probabilities. If we succeed in learning how to forecast accurately for a few minutes ahead, we will attempt to incorporate an appropriate alsorithm into the Mod-OA microprocessor controller. Because of the limitations imposed by our microprocessor we have narrowed our study to a Holt-Winters type alogrithm (Granger, 1977).

The yaw system question is quite similar. Presently the Mod-OA yaw mechanism is activated whenever the 20-second (electronically) averaged yaw error exceeds 25 degrees. The yaw drive then rotates the nacelle until the yaw error is reduced to 18 degrees. If the start/stop study discussed above produces the desired results, a similar study will be undertaken to find the optimum trade-off between increased efficiency resulting from improved alignment vs. increased wear resulting from excessive yawing maneuvers.

FATIGUE LOADING

As part of the design process for WTs various simulation models are used which predict loads on the rotor blades as a function of wind speed. These are directly measured parameters on the Mod-OA. Figure 7 shows an example of the flap-wise bending moment near the blade root as a function of the wind speed measured at the nacelle. Spera, in his talk this morning, showed a similar comparison of theory with these experimental data (Spera, 1979).

This is an example of a static calculation, i.e., the calculation estimates the WT response to a steady wind. The effects of gusts are more complicated. The model used to allow for gusts is described elsewhere (Frost, 1978). Some effort at verifying the gust model used will be made in cooperation with PNL as part of their analysis of the meteorological tower data described above. A complimentary effort will be undertaken at the Lewis Research Center as an extension of the time series analysis discussed above.

One further area requiring the application of wind data is the estimation of lifetime fatigue loads on a WT, with particular emphasis on blade lifetimes. It would be highly desireable to periodically sample the performance data from a WT and be able to either predict the probable machine lifetime, or detect changes in operating characteristics. Simply looking at absolute levels of the measured parameters will not suffice. The parameters of interest are highly interdependent and are all driven to a greater or lesser degree by the wind. At the very least, it will be necessary to normalize all data with respect to some "standard" wind profile.

CONCLUSIONS

In an R&D environment, both design evaluation and power performance optimization require the continuous monitoring of wind data. Some peogress has been made in understanding the data collected thus far. However, the high degree of variability of the wind in speed and direction with both time and space, imposes the need to further develop statistical models for the extraction of all the information desired by the WT developers.

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TABLE I. - 200 KILOWATT WIND TURBINE SPECIFICATIONS

Rotor

Number of blades	2
Diameter, ft	125
Speed, rpm	40
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable Pitch
Cone angle, deg	7
Tilt angle, deg	0

Blade

Length, ft	59.9
Material	Aluminum
Weight, lb/blade	2300
Airfoil	NACA 23000
Twist, deg	26.5
Solidity, percent	3
Tip chord, ft	1.5
Root chord, ft	4
Chord taper	Linear

Tower

Type	Pipe truss
Height, ft	93
Ground clearance, ft	37
Hub height, ft	100
Access	Hoist

Transmission

Type	Three-stage conventional
Ratio	45:1
Rating, hp	460

Generator

Type	Synchronous ac
Rating, kVA	250
Power factor	0.8
Voltage, V	480 (three phase)
Speed, rpm	1800
Frequency, Hz	60

Orientation drive

Type	Ring gear
Yaw rate, rpm	1/6
Yaw drive	Electric motors

Control system

Supervisory	Microprocessor
Pitch actuator	Hydraulic

Performance

Rated power, kW	200
Wind speed at 30 ft, mph (at hub):	
Cut-in	6.9 (9.5)
Rated	18.3 (22.4)
Cut-out	34.2 (40)
Maximum design	125 (150)

Weight (klb)

Rotor (including blades)	12.2
Above tower	44.9
Tower	44.0
Total	88.9

System life

All components, yr	30

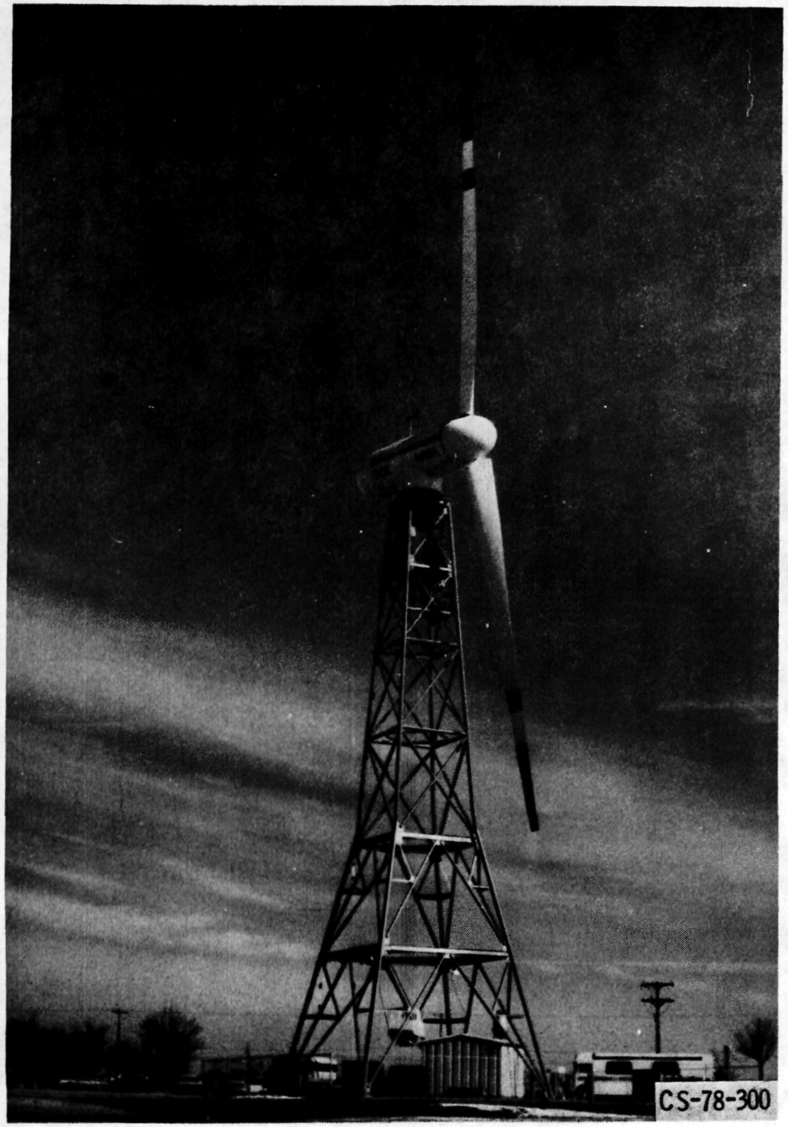

Figure 1. - 200-Kilowatt wind turbine.

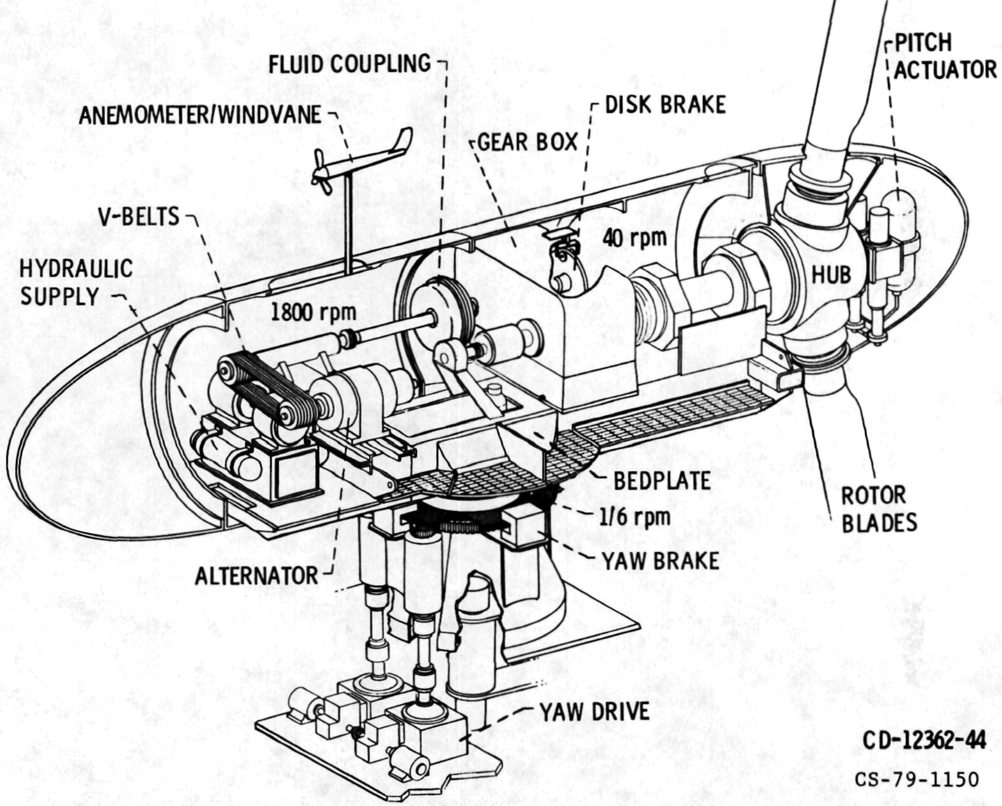

Figure 2. - Cutaway drawing of tower mounted equipment.

Figure 3. - Overall view of Clayton wind turbine site.

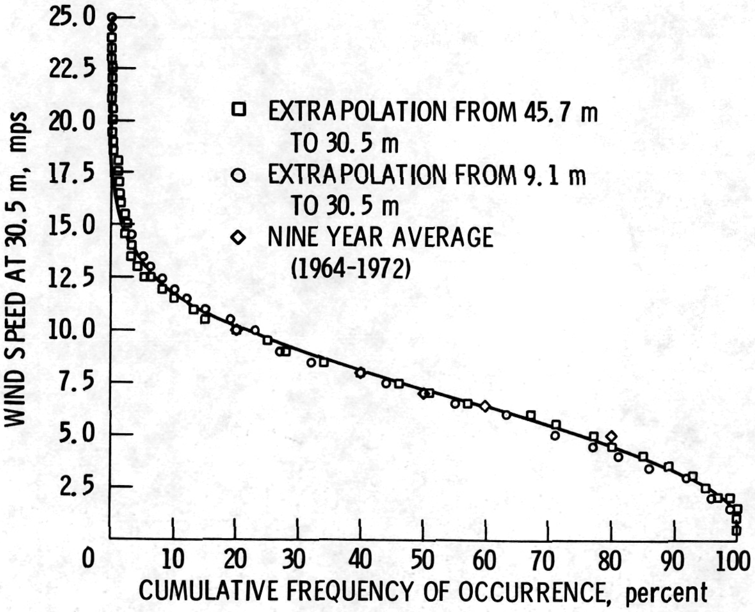

Figure 4. - Clayton, New Mexico Meterological Tower Data from September 1977 to August 1978. Data Source: WSSI Monthly.

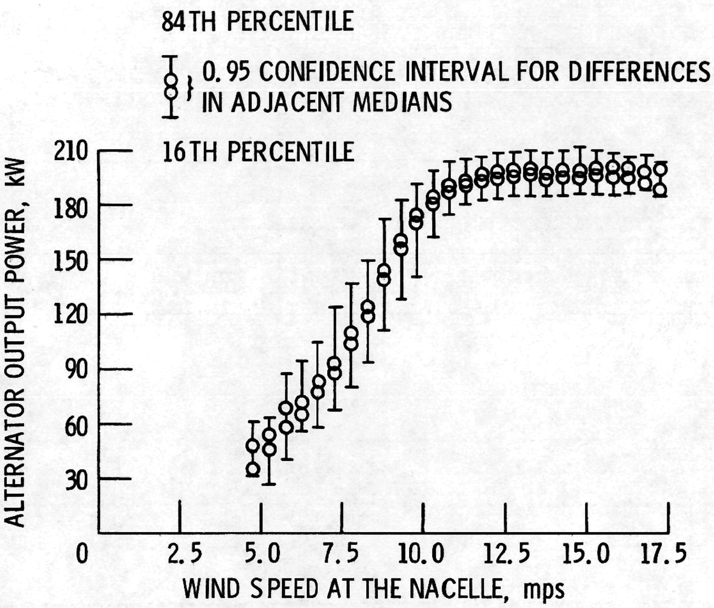

Figure 5. - Power performance data for 3 1/2 hours from the Clayton, New Mexico Wind Turbine on January 7, 1978.

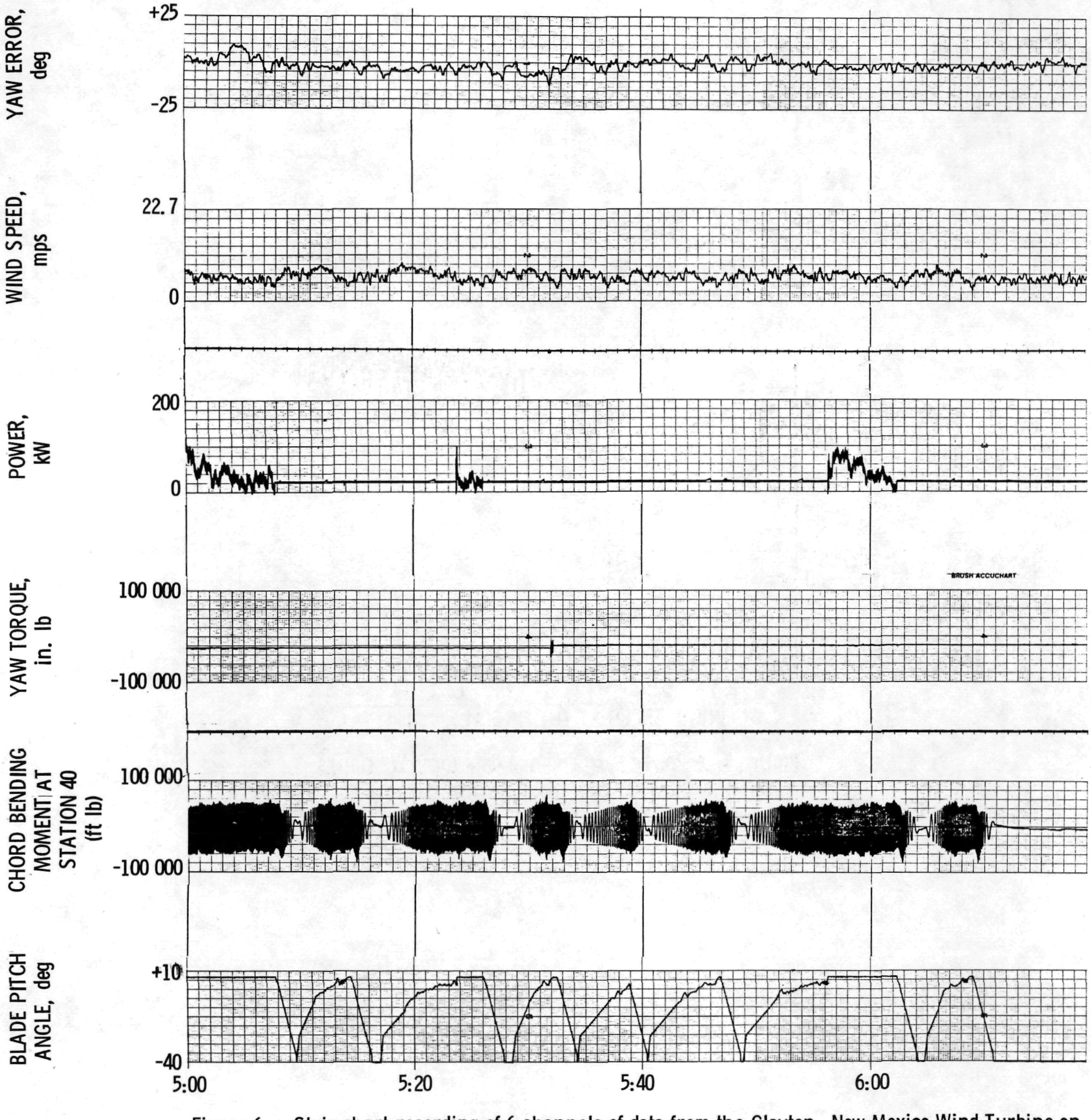

Figure 6. - Strip chart recording of 6 channels of data from the Clayton, New Mexico Wind Turbine on the afternoon of February 15, 1979.

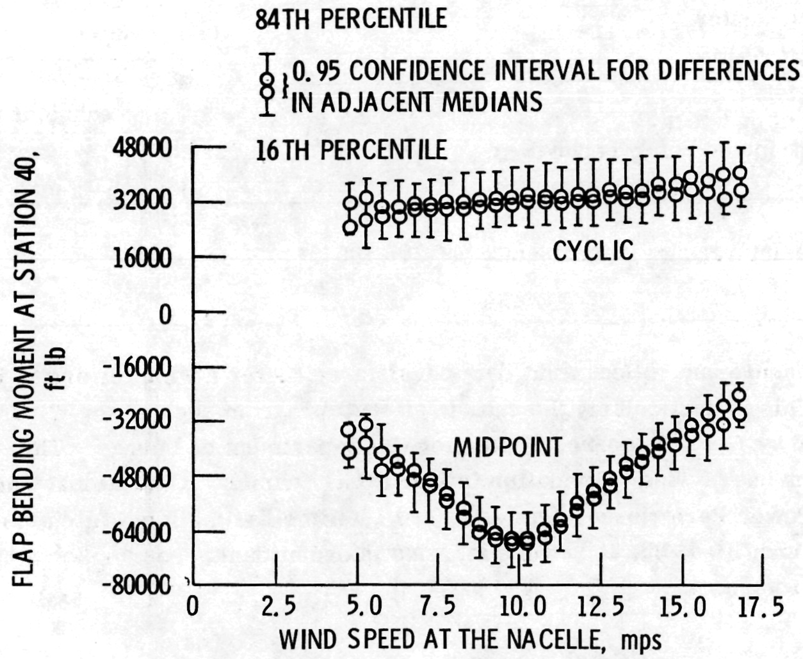

Figure 7. - Blade load data for 3 1/2 hours from the Clayton, New Mexico, Wind Turbine on January 7, 1978.

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16. Abstract

The need to measure and collect wind data persists well after a wind turbine is initially made operational. This is particularly the case in an R&D program such as the Wind Energy Project being conducted by Lewis Research Center for the Department of Energy. This report presents the status of our use of wind information in four areas, namely: Operational Control, Design Verification, Power Performance Analysis, and Lifetime Estimation. Attention is also given to some of the identified, but as yet unmet, wind informational needs and the steps we plan to take to meet these needs.

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